(学位申請論文)　　　　　　論文目録

主論文

1. 題目　Anomalous Propagation of Trans-equatorial VLF Radio Waves in the Geomagnetically Quiet and Disturbed States.
(地磁気静穏時および擾乱時における赤道越えVLF電波の異常伝搬)

2. 公表の方法・時期
1部　Anomalous Diurnal Changes of Trans-equatorial VLF Radio Waves.
(赤道越えVLF電波の異常日変化)
Journal of Atmospheric and Terrestrial Physics, 1973年掲載予定
2.部　Anomalous Phase Changes of Trans-equatorial VLF Radio Waves during Geomagnetic Storms.
(磁気嵐時における赤道越えVLF電波の異常位相変化)
Journal of Geophysical Research, 1973年「掲載予定

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1. 題目　Propagation of weak hydromagnetic shock waves in the exosphere and geomagnetic variations due to high altitude nuclear explosion
(外気圏内の弱い衝撃波の伝搬と超高層核爆発による地磁気変化).
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2. 題目　Propagation of weak hydromagnetic discontinuity in the magnetosphere and the sudden commencement of geomagnetic storms (磁気圏内の弱い磁気流体不連続面の伝搬と磁気嵐急始部).
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3. 題目　Diurnal variations of the size of the magnetosphere (磁気圏の大きさの日変化),
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4. 題目　Magnetic field oscillations near the earth's bow shock (磁気圏バウショック付近の磁場変動).
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(オーストラリアからのVLF電波の赤道越え受信),. Radio Science, Vol.4, 4, 367-369, 1969掲載
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(VLF電波の電離層反射係数におよぼすイオンの効果),
Contributions of Geophysical Institute, Kyoto University, No.11, 1-10, 1971掲載
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(オーストラリアのVLF電波送信局からのホイッスラーモード波の検出),
The Report of Ionosphere and Space Research in Japan, Vol.26, 1/2, 69-78, 1972掲載
: 内藤悠史, 加藤進と共著
8. 題目　電離層におけるnon-reciprocalな電波伝搬, 物性研究, Vol.18, 6, 338-348, 1972掲載

昭和48年 3月 2日

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主論文要旨

主論文１部では，日本とマダガスカルで観測されたオーストラリアからのVLF標準電波の強度と位相を,アメリカとアルゼンチンで観測されたパナマの電波と比較検討し，赤道越えVLF電波に共通な日変化異常の存在を指摘した。

ついで，この日変化異常が，(1) 地球-電離層導波管内に昼間は第一モードのみが，夜間には第一,第二モードが存在する，(2) 夜の磁気赤道付近で，interference distance が異常分布している，と仮定することにより，定量的に説明できることを証明し，この異常な interference distance の周波数変化を計算で求めた。

2部では，宇治で観測したオーストラリアのVLF標準電波の位相記録を調べ，大きな磁気嵐の主相時に，この位相が異常変化することを発見し，磁気嵐の影響が低緯度下部電離層に及び得ることを世界で初めて指摘した。又，この位相変化の向きから，下部電離層の実効反射高が増加していると推定した。

学位授与申請者

荒木　徹

主論文

Anomalous Propagation of Trans-equatorial VLF Radio Waves in the Geomagnetically Quiet and Disturbed States.

1部　Anomalous Diurnal Changes of Trans-equatorial VLF Radio Waves.

2.部　Anomalous Phase Changes of Trans-equatorial VLF Radio Waves during Geomagnetic Storms.

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第１部 Anomalous Diurnal Changes of Transequatorial V.L.F. Radio Waves

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Abstract

The reception in Japan of the VLF radio waves transmitted from NWC (15.5, 18.0, 19.8 and 22.3 kHz, Australia) reveals anomalous diurnal changes of the field intensity and the phase which are especially notable at 19.8 kHz, and of a similar nature to the observation of NBA signals (18.0 kHz, Panama) in Argentina. These are consistently explained by a model which is essentially the same as that used for the interpretation of anomalous sunrise fading pattern of NPG signals (18.6 kHz, Seattle, U.S.A.) observed in Australia and New Zealand. The interference distance, D, in the nighttime earth-ionosphere waveguide is assumed to decrease from the maximum value, D_{max}, at the geomagnetic equator to the normal value at ± 20° of the geomagnetic latitude. Values of D_{max} are sought which can best explain the observed anomalous diurnal changes of the field strength. Two values of D_{max} for 18.0 kHz which are derived

independently from two values of the diurnal changes of the field intensity observed at Japan and Argentina agree within an observational error. These are also nearly equal to D_{max} obtained from the analysis of anomalous sunrise fading by Lynn. Anomalous diurnal changes of the phase observed at both stations can also be explained qualitatively by this model.

1. Introduction

Chilton et al. (1964) made simultaneous observations of the frequency stabilized VLF signals from Canal zone, Panama (NBA, 18 kHz) both in the northern hemisphere (Boulder, Colorado, U.S.A.) and in the southern hemisphere (Tucuman, Argentina). The two propagation paths are of approximately equal length (about 4300 km) and have similar bearing to the geomagnetic field line (Fig. 1). The notable difference is that the one path (NBA to Boulder) lies wholly in the northern hemisphere while the other (NBA to Tucuman) crosses the geographical and the geomagnetic equator from the northern to the southern hemisphere. They compared the data from the two stations and found large differences in the diurnal changes of the phase and the field intensity. Their observational results are summerized as follows;

(1). the field intensity at Tucuman is approximately 12 db greater during the daytime than at night, while the nighttime field intensity at Boulder is on the average 3 db greater than the daytime intensity (Fig. 2(b)), (2). the estimated nighttime field intensity is about 17 db less at Tucuman than at Boulder,

(3). the nighttime signals at Tucuman are considerably more disturbed than at Boulder,

(4). though the diurnal phase change at Boulder is consistent with that predicted by waveguide mode theory in which it is assumed that only the first order mode is propagated and that there is a diurnal change of ionospheric height of 17 km, the diurnal phase change at Tucuman is about 30 per cent less than at Boulder. Chilton et al. suggested that the anomalous diurnal changes at Tucuman could possibly be due to a difference in ionization profile resulting from latitudinal dependence of cosmic-rays.

The new VLF station NWC (North West Cape, Australia) began to transmit phase-stabilized signals in September, 1967, with the test frequencies of 15.5, 18.0, 19.8 and 22.3 kHz changing once a week. Ishii et al. (1968) continuously observed the phase and the field intensity of NWC signals at Inubo, Japan (Fig. 1), and reported that the nighttime field intensity is somewhat lower for 15.5 kHz and somewhat higher for 22.3 kHz but much weaker (about 10 db) for 19.8 kHz than the daytime intensity (Fig. 2(a)). Further they noticed that the size of the diurnal phase change is anomalously larger for 19.8 kHz than for 15.5 kHz and 22.3 kHz (Fig. 3). This is directly contrary to the phase behavior observed at Tucuman. Similar observations for 15.5 kHz and 22.3 kHz was made also at Uji, Japan, and the results were consistent with those at Inubo (Araki et al. 1969). Thus it can be said that the anomalous diurnal changes of the VLF phase and field intensity are seen commonly along transequatorial propagation paths, but it depends strongly upon frequency and propagation path length.

Lynn (1971) also made the observation of the field intensity of NWC signals at Tananarive, Madagascar (Fig. 1). The propagation path length between NWC and Tananarive (about 6900 km) is almost the same as NWC-Inubo path (about 6990 km) and we can directly compare the observations made along the two paths. In Figure 2(a) is plotted the size of the diurnal change of the field intensity observed at Inubo (thick line) and Tananarive (thin line). It shows a clear discrepancy of the diurnal changes of the field intensity between the two receiving sites especially around the frequency of 20 kHz.

There are other anomalous changes of VLF signals observed along transequatorial paths. When the intersection of a sunrise line and a propagation path is near the geomagnetic equator, the sunrise fading in the field intensity becomes deep and the fading period becomes long. Further so called cycle slipping occurs easily at this time of the sunrise period. These phenomena were mainly analysed using 18.6 kHz signals from NPG/NLK (Seatlle, Washington, U.S.A.) observed at Australia (Lynn, 1967, 1969) and New Zealand (Kaiser, 1968). Lynn (1970) succeeded in explaining the phenomena by assuming an anomalous distribution for the nighttime interference distance, D (Crombie, 1964), and the mode conversion ratio within ± 20° of the geomagnetic latitude.

If the anomalous distribution of the nighttime interference distance which is observed during the sunrise period persists through a night, the nighttime field intensity and the relative phase observed along a transequatorial path would also show anomlaous behavior and the size of the diurnal change of the field intensity and the phase would be different from what we could expect from the normal distribution for D. On the basis of this speculation, we also adopt the model that D begins to deviate from the normal value at ± 20° of the geomagnetic latitude and increases toward the geomagnetic equator and try to explain the anomalous diurnal changes of VLF signals observed at Tucuman and Japan by the use of this model.

2. The Model and Calculation

The vertical electric wave field transmitted from a vertical electric dipole in the earth-ionosphere waveguide is generally given (Wait, 1962, Rohoads and Garner, 1967) by

$$E = \frac{E_0}{h} \sum_m |\Lambda_m| e^{-\alpha_m x} e^{i\omega(t-\frac{x}{v_m}) + i \arg \Lambda_m} \qquad (1)$$

where

m = mode number,

Λ_m = excicitation factor of mode m at a transmitter,

α_m = attenuation rate of mode m,

v_m = phase vlocity of mode m,

x = distance from a transmitter to a receiver,

h = effective reflection height of the ionosphere,

ω = wave angular frequency,

E_0 = a constant determined by f, x and transmitted power.

In equation (1) it is assumed that the transmitter and the receiver are on the ground and so the height gain factors are taken to be unity.

If the attenuation rate α_m and the phase velocity v_m vary slowly along the propagation path, equation (1) may be replaced by

$$E = \frac{E_0}{h} \sum_m |\Lambda_m| \, e^{-\int_0^x \alpha_m dx} \, e^{i\omega\left(t - \int_0^x \frac{dx}{v_m}\right) + i \arg \Lambda_m} \tag{2}$$

It is assumed here that during the daytime there exists only the first order mode in the earth-ionosphere waveguide and during the nighttime both of the first and the second order modes are propagated. Then the wave field in the day and night, E_D and E_N, are given by the real part of equation (2) as

$$\begin{aligned} E_D &= E_{D0} \cos(\omega t - \theta_D) \\ E_N &= E_{N1} \cos(\omega t - \theta_{N1}) + E_{N2} \cos(\omega t - \theta_{N2}) = E_{N0} \cos(\omega t - \theta_N) \end{aligned} \tag{3}$$

where

$$E_{D0} = \frac{E_0}{h_D} |\Lambda_{D1}| \, e^{-\int_0^x \alpha_{D1} dx} \tag{4a}$$

$$\theta_D = -\omega \int_0^x \frac{dx}{V_{D1}} + \arg \Lambda_{D1} \tag{4b}$$

and

$$E_{N1} = \frac{E_0}{h_N} |\Lambda_{N1}| \, e^{-\int_0^x \alpha_{N1} \, dx}$$

$$\theta_{N1} = -\omega \int_0^x \frac{dx}{V_{N1}} + \arg \Lambda_{N1}$$

$$E_{N2} = \frac{E_0}{h_N} |\Lambda_{N2}| \, e^{-\int_0^x \alpha_{N2} \, dx} \tag{5}$$

$$\theta_{N2} = -\omega \int_0^x \frac{dx}{V_{N2}} + \arg \Lambda_{N2}$$

and

$$E_{N0} = \left\{ E_{N1}^2 + E_{N2}^2 + 2E_{N1}E_{N2}\cos(\theta_{N1} - \theta_{N2}) \right\}^{\frac{1}{2}} \tag{6a}$$

$$\theta_N = \theta_{N1} - \tan^{-1} \frac{E_{N2} \sin(\theta_{N1} - \theta_{N2})}{E_{N1} + E_{N2} \cos(\theta_{N1} - \theta_{N2})} \tag{6b}$$

The factor $(\theta_{N1} - \theta_{N2})$ in equation (6) can be expressed as

$$\theta_{N1} - \theta_{N2} = -2\pi \int_0^x \frac{dx}{D} + \arg(\Lambda_{N1}/\Lambda_{N2}) \tag{7}$$

where D is the interference distance in the nighttime waveguide (Crombie, 1964) which is given by

$$D = \frac{2\pi V_{N1} V_{N2}}{\omega (V_{N2} - V_{N1})} \tag{8}$$

The size of the diurnal change of the field intensity,

$$\Delta E = E_{N0} - E_{D0}, \tag{9}$$

can be calculated from equations (4a) and (6a). Propagation parameters (excitation factor, attenuation rate, and phase velocity) necessary to the calculation of E_{N0} and E_{D0} are provided by Wait and Spies (1964) in which they assumed that the ionospheric conductivity parameter, ω_r, varies exponentially with height as

$$\omega_r = \omega_{r0} \exp(\beta(h - h_0)). \tag{10}$$

The dotted curve in Fig. 2(a) is the results of Lynn's calculation for ΔE for the NWC-Tananarive path in which h_0 and β are taken to be 70 km and 0.3 km^{-1} for the daytime ionosphere and 90 km and 0.5 km^{-1} for the nighttime. For the propagation path length of NBA-Boulder and NBA-Tucuman, ΔE was calculated by the use of the same combination of h_0 and β and plotted in Fig. 2(b) Propagation parameters used in the calculation are listed in Table 1.

As seen from Figs. 2(a) and 2(b), calculated values for the size of the diurnal variations of the field intensity agree fairly well with observations both at Tananarive and Boulder. Thus we assume that the ionosphere along the two non-transequatorial propagation paths in the middle latitude (NBA-Boulder and NWC-Tananarive) is in the normal condition which is prescribed by equation (10) with the values of β and h_0 listed in Table 1. For the transequatorial propagation paths (NBA-Tucuman and NWC-Inubo), a model is adopted which is essentially the same as that of Lynn (1970); that is, the daytime ionosphere is normal but in the nighttime the interference distance, D, varies with latitude in the region within $\pm$ 20° of the geomagnetic latitude as shown by Fig. 4. The dependence of D upon the distance, x, from the geomagnetic equator along a propagation path is assumed to be given by

$$\left(\begin{aligned} D &= (a^2 - x^2)^{\frac{1}{2}} - y_0 \\ a &= \frac{X_0^2 + (D_{Max}^2 - D_0^2)}{2(D_{max} - D_0)} \\ y_0 &= \frac{D_{max}^2 - (D_0^2 + D_x^2)}{2(D_{max} - D_0)} \end{aligned} \right) \qquad (11)$$

where D_0 is the normal D value which is calculated by equation (8) using the phase velocity listed in Table 1, and D_{max} is the D value at the equator, and x_0 is the distance from the equator to the points of $\pm$ 20° of the geomagnetic latitude along the propagation path. The attenuation rate in the anomalous region is assumed to be constant or vary so slowly that it has little effects on the observed anomalous behavior of the diurnal variations of VLF signals.

For a given value of D_{max}, the latitudinal variation of D is determined by equation (11) and the size of the diurnal variation of the field intensity, ΔE, can be calculated using equations (3)-(9). In this way, values of D_{max} are sought which give ΔE best fitted to the observations at Inubo and Tucuman. The results are shown in Fig. 5. For the frequency 18.0 kHz, two values of D_{max} are obtained from the observed ΔE at Inubo and Tucuman, but it can be said that they agree within an observational error. In Fig. 5 is also plotted a value of D_{max} estimated by Lynn (1970) from the anomalous sunrise fading pattern of 18.6 kHz signals from NPG/NLK to Australia. It also agrees well with the present results.

The values of D_{max} in Fig. 5 are calculated from the observed diurnal changes of the field intensity at Inubo and Tananarive. A question which arises here is whether this model with D_{max} values in Fig. 5 could explain anomalous behavior of the diurnal phase changes observed at the two stations. In order to answer this question, the size of the diurnal variations of the phase,

$$\Delta\theta = \theta_D - \theta_N, \tag{12}$$

is calculated for both normal and abnormal ionospheric conditions. Here "normal ionosphere" means the ionosphere prescribed by the exponential height profile for the conductivity parameter with the values of β and h_0 listed in Table 1, and "abnormal ionosphere" is specified by Lynn's model and equation (11) and D_{max} in Fig. 5. The results of the calculation and the observations are summarized in Table 2. For the propagation distance of 4300 km, calculated values themselves ($\Delta\theta_{abnormal}$ and $\Delta\theta_{normal}$) are somewhat larger than the observed values ($\Delta\theta_{Tucuman}$ and $\Delta\theta_{Boulder}$) but the calculated results that $\Delta\theta_{abnormal}$ is about 30 per cent less than $\Delta\theta_{normal}$, agree with the observational fact that on the average $\Delta\theta_{Tucuman}$ is 30 per cent less than $\Delta\theta_{Boulder}$. For the propagation distance of 7000 km, we have no non-transequatorial path which should be compared with the observed results at Inubo because at Tananarive no observation of the relative phase was made. The phase observed at Inubo, however, clearly shows anomalously large diurnal variations at 19.8 kHz. The values calculated for the abnormal ionosphere model ($\Delta\theta_{abnormal}$) are somewhat larger than observed $\Delta\theta$ except for 22.3 kHz for which the discrepancy is very large, but their ratios to the values for the normal ionosphere ($\Delta\theta_{normal}$) show a tendency that the anomaly is most pronounced at 19.8 kHz. This agrees well with the observations. The large discrepancy between the calculation and observation for 22.3 kHz seems to originate from 180° ambiguity of arc-tangent in equation (6b).

3. Discussions

We assumed that the ionosphere is normal in the daytime and abnormal in the nighttime. This assumption seems to be reasonable because the structure of the daytime ionosphere is determined almost only by the dominant solar radiation while there are some questions of the maintenance of the nighttime lower ionosphere and we might expect unknown agents which causes the anomalous ionosphere in the nighttime.

The validity of the isotropic exponential model for the conductivity parameter was discussed by Lynn (1970) in some details. The point of the discussion is that the new modes of mixed polarization ranging from TM and TE in character appear by taking the geomagnetic field into the earth-ionosphere wave-guide mode theory. The introduction of the new modes might modify the results computed from the isotropic exponential model. The observations at Tananarive and Boulder, however, are more in agreement with the calculation from the isotropic exponential model rather than that from these recently developed theories.

The isotropic exponential model is also supported by field intensity measurements for several frequencies using the airplane (Rhoad and Garner, 1967), but this experiments show that the first two or three modes should be important out to distances greater than 3000 km even in the daytime. The amplitude of the undulations of the field intensity curves versus distance in their graphs, however, becomes small in the range greater than 4000 km. This shows that the higher order modes are rapidly attenuated with increasing distance and the neglect of them would not cause great errors.

Rohads and Garner took 0.5 km^{-1} as a value of daytime β while we had to take 0.3 km^{-1} in order to reconcile with the observations at both of Boulder and Tananarive. The cause of this discrepancy has not yet known and remains to be studied in future.

Wait and Spies (1964) gave propagation parameters only for combinations of (h_0, β) with h_0 = 60, 70, 80, 90 km and β = 0.3 and 0.5 km^{-1}. A combination of (h_0, β) which is different from that used here and gives better agreement between the observation and calculation might possibly be obtained if the propagation parameters were calculated for more detailed h_0 and β.

The dependence of the anomalous D values upon distance along the propagation path is assumed to be the circular form (eq. 11). The choice of this form is rather arbitrary. The parabolic form was tested and it was found that the circular form is better but the results are not so sensitive to functional form of D.

It might seem that there is no ground to justify the neglect of the change of the attenuation rate along the propagation path in the region of the abnormal ionosphere. The curve of ΔE versus distance for the normal ionosphere, which is not shown here, shows rapid variation in the range from 4000 km to 10000 km especially for the frequencies of 18.0 and 19.8 kHz and the observed values of ΔE might be explained only by moving the curves parallel to the abscissa. This may be realized by changing D values without change of attenuation rate. Thus it is considered that the anomaly in D plays a primary role and any change of the attenuation rate is rather secondary in importance.

4. Conclusion

Lynn (1970) used the model that the interference distance D in the nighttime is anomalously distributed within ± 20° of the geomagnetic latitude in order to explain the anomalous sunrise fading pattern of VLF signals observed along the transequatorial propagation path (NPG/NLK (18.6 kHz) to Australia).

This model is applied to the anomalous diurnal changes observed along the two transequatorial paths; NBA (Panama, 18.0 kHz) to Tucuman (Argentina) and NWC (Australia, 15.5, 18.0, 19.8, 22.3 kHz) to Inubo (Japan). It is assumed that D takes the maximum value at the geomagnetic equator and decreases to the normal value at ± 20° of the geomagnetic latitude. The dependence of D upon the distance from the geomagnetic equator is assumed to be circular within ± 20° of the geomagnetic latitude. For four frequencies observed at Inubo and one frequency at Tucuman, the maximum values of D at the equator, D_{max}, are calculated which can explain best the observed anomalous diurnal changes of the field intensity at the two stations. Two values of D_{max} are obtained from two values of observations at Inubo and Tucuman for the frequency of 18.0 kHz. They show a fairly good agreement within an observational error. They also agrees well with D_{max} calculated by Lynn for the explanation of the anomalous behavior of 18.6 kHz signals during sunrise.

This model with values of D_{max} calculated from the observed diurnal changes of the field strength is used to compute the diurnal changes of the relative phase, $\Delta\theta$, for the observed frequencies at the both stations. Though the values of $\Delta\theta$ themselves are somewhat different from observed values, they show the same tendency as the observations that $\Delta\theta$ is anomalously small at Tucuman for 18.0 kHz and anomalously large at Inubo for

19.8 kHz.

We may, therefore, reasonably conclude that the anomalous diurnal changes of the field intensity and the phase of VLF radio waves observed along transequatorial propagation paths can be consistently explained by the model which is essentially the same as that used for the interpretation of the anomalous sunrise fading pattern of VLF signals observed also along transequatorial paths.

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Figure Captions

Fig. 1 Propagation paths used for analysis of anomalous diurnal changes (solid line) and sunrise fading (dashed line) of VLF radio waves.

Fig. 2 The size of the diurnal changes of the field intensity of NWC(a) and NBA(b) signals. A dotted line of (a) and a cross mark of (b) show calculated values from the isotropic exponential model for the ionospheric conductivity parameter.

Fig. 3 The averaged diurnal phase variations of NWC signals observed at Inubo, Japan. Dark portion under the each figure shows a period during which the entire propagation path is in nightside and hatched portion shows a period during which the path is divided into day and night. (after Ishii et al.).

Fig. 4 Anomalous distribution of the interference distance, D, used for the calculation of the anomalous diurnal changes of the field intensity of transequatorial VLF radio waves.

Fig. 5 Values of D_{max} which can best explain the anomalous diurnal changes of the field intensity observed at Inubo (solid circle) and Tucuman (triangle). The cross shows the value obtained from analysis of anomalous sunrise fading pattern by Lynn. The normal D values (open circle) are calculated from the isotropic exponential model for the ionospheric conductivity parameter.

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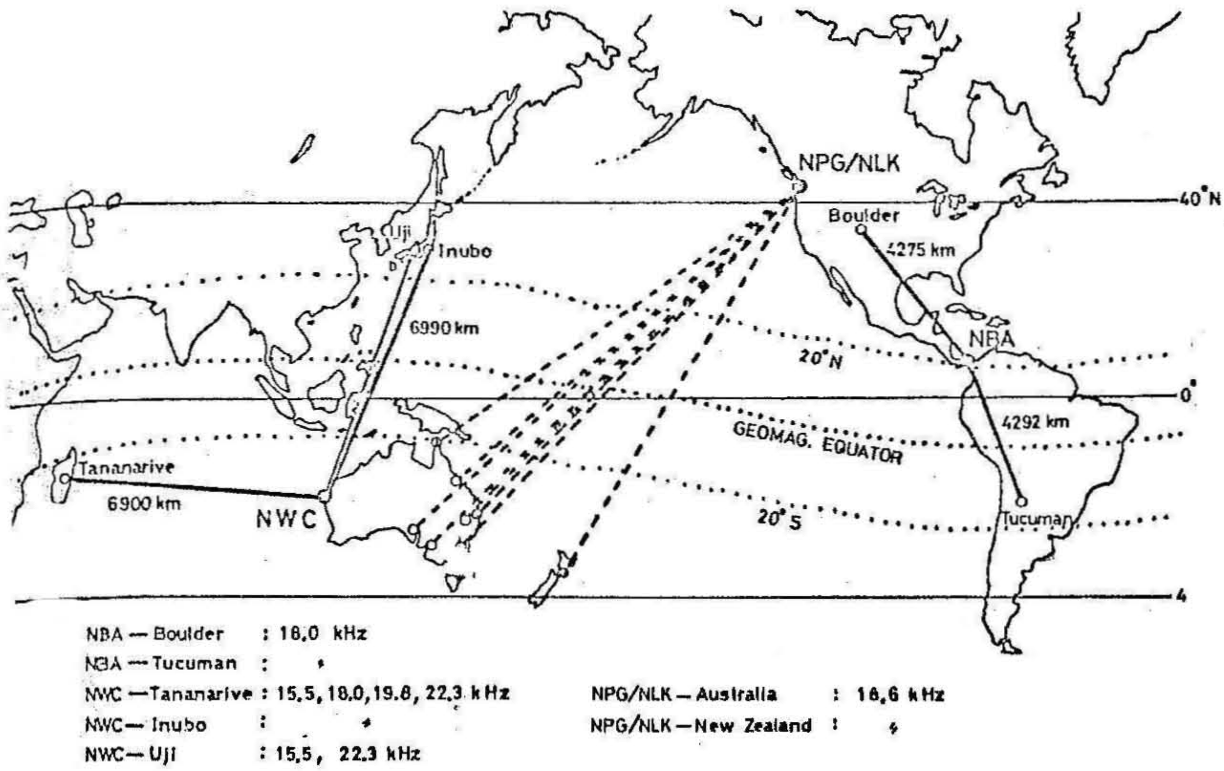
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Boulder
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Uji
Inubo
6990 km
NBA
20°N
4292 km
GEOMAG. EQUATOR
Tananarive
6900 km
NWC
20°S
Tucuman
40°N
0°
NBA — Boulder : 18.0 kHz
NBA — Tucuman : "
NWC — Tananarive : 15.5, 18.0, 19.8, 22.3 kHz
NWC — Inubo : "
NWC — Uji : 15.5, 22.3 kHz
NPG/NLK — Australia : 18.6 kHz
NPG/NLK — New Zealand : "

Fig. 1

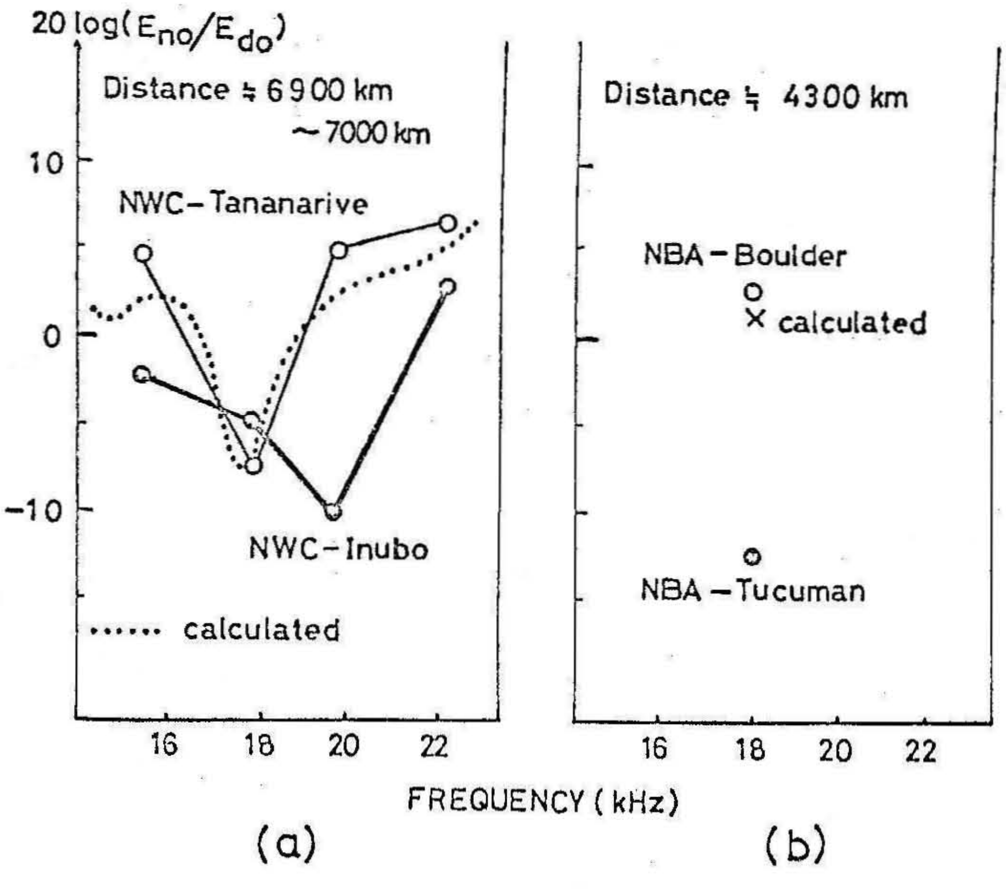
20 log(E_{no}/E_{do})
Distance ≒ 6900 km
~7000 km
10
0
-10
NWC-Tananarive
NWC-Inubo
calculated
16
18
20
22
Distance ≒ 4300 km
NBA-Boulder
× calculated
NBA-Tucuman
FREQUENCY (kHz)
(a)
(b)

Fig. 2

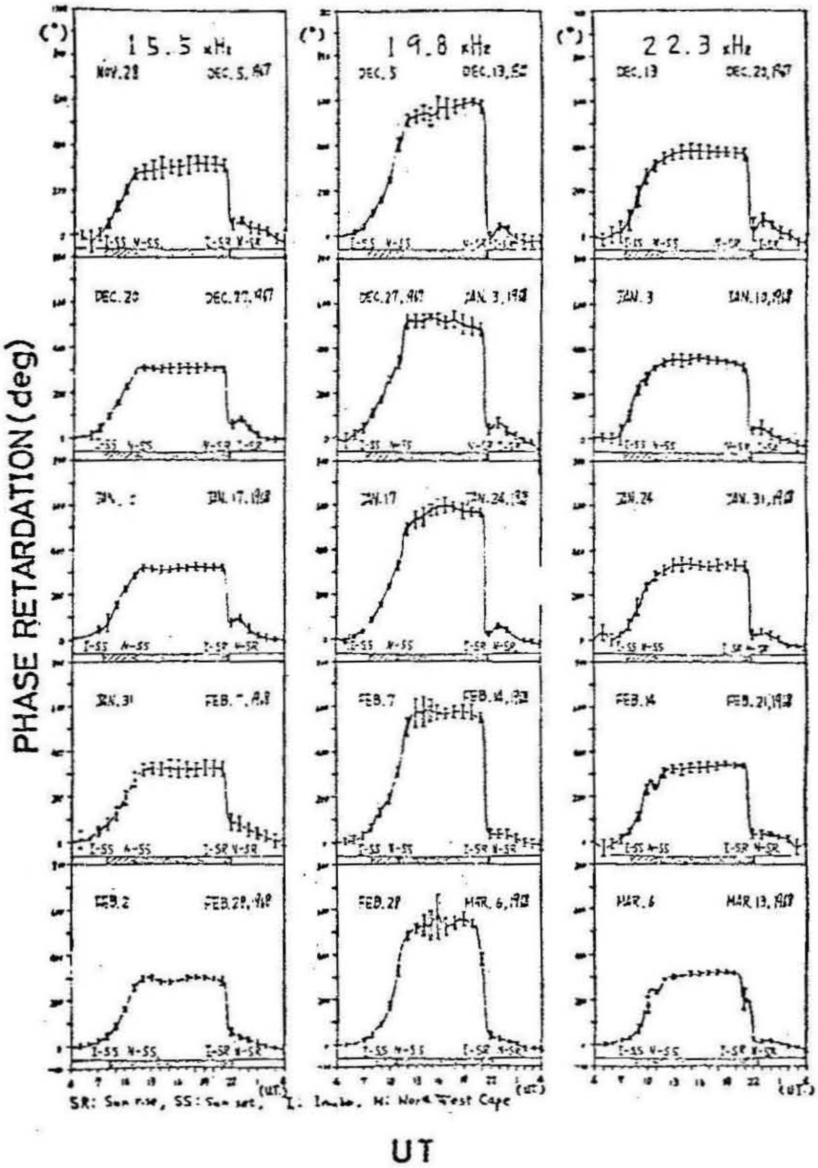
PHASE RETARDATION (deg)
15.5 kHz
19.8 kHz
22.3 kHz
SR: Sun rise, SS: Sun set, I: Inubo, N: North West Cape
UT

Fig. 3

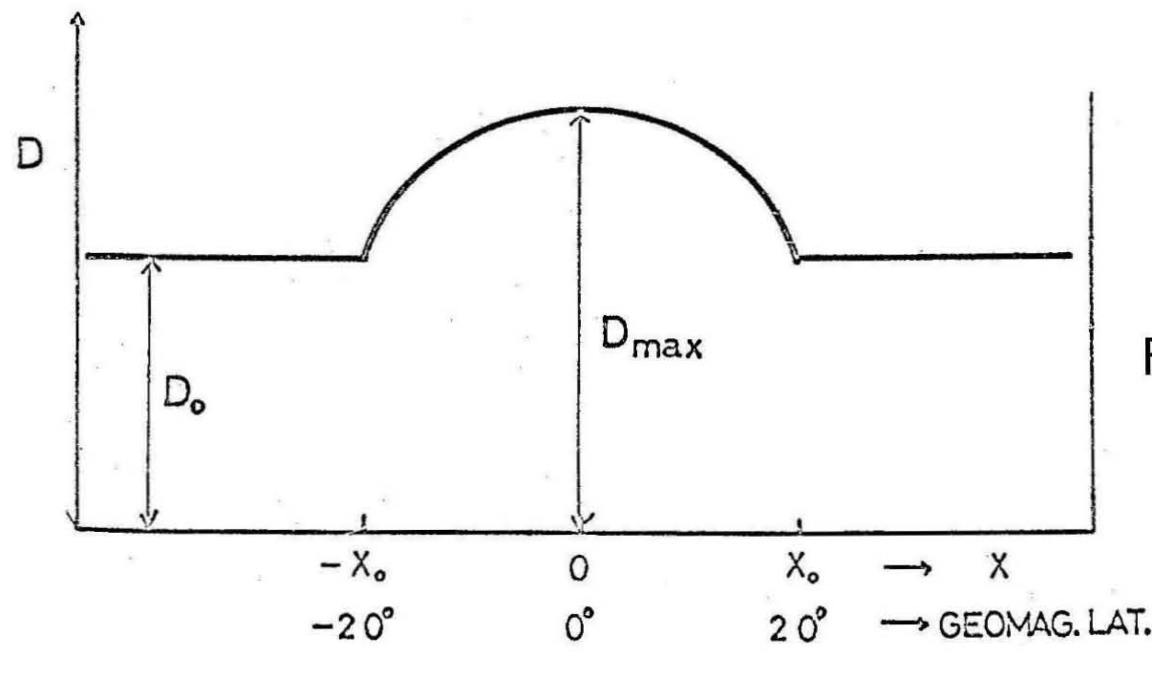
D
D_o
D_{max}
$-X_o$
0
X_o
→ X
−20°
0°
20°
→ GEOMAG. LAT.

Fig. 4

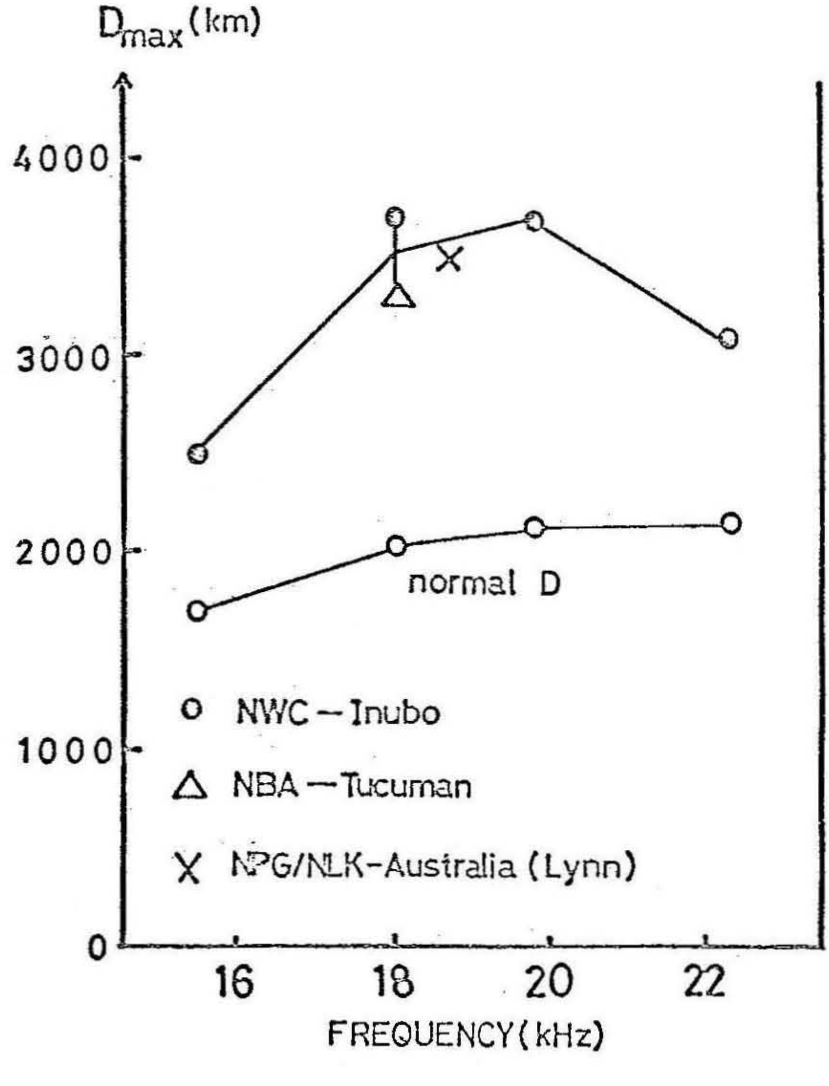
D_{max}(km)
4000
3000
2000
1000
0
normal D
o NWC — Inubo
△ NBA — Tucuman
X NPG/NLK-Australia (Lynn)
16
18
20
22
FREQUENCY(kHz)

Fig. 5

Propagation Parameter	Frequency (kHz) 15.5	18.0	19.8	22.3	h_0 (km)	β (km^{-1})
α_{D1} ($dB/10^3 km$)	2.5	2.4	2.5	2.7	70.0	0.3
v_{D1} ($10^5 km/sec$)	2.9979250	2.9955266	2.9943275	3.0033213		
$\|\Lambda_{D1}\|$ (dB)	-0.4	-1.0	-1.6	-2.5		
$\arg\Lambda_{D1}$ (deg)	7.5	9.0	10.2	12.5		
α_{N1} ($dB/10^3 km$)	1.3	1.5	1.7	2.0	90.0	0.5
v_{N1} ($10^5 km/sec$)	2.9889312	2.9868327	2.9856335	2.9835350		
$\|\Lambda_{N1}\|$ (dB)	-5.0	-7.4	-10.0	-11.9		
$\arg\Lambda_{N1}$ (deg)	9.1	11.8	14.2	18.2		
α_{N2} ($dB/10^3 km$)	4.2	3.5	3.1	2.7		
v_{N2} ($10^5 km/sec$)	3.0231076	3.0114157	3.0069183	3.0021221		
$\|\Lambda_{N2}\|$ (dB)	2.1	2.3	2.5	2.3		
$\arg\Lambda_{N2}$ (deg)	1.2	1.5	2.0	3.0		

Table 1

Propagation parameters (attenuation rate (α), phase velocity (v) and excitation factor (Λ)) used for the calculation.

Propagation Distance (km)	Frequency (kHz)	15.5	18.0	19.8	22.3
~ 7000	$\Delta\theta_{Inubo}$ (observed)	$310°-340°$		$540°-600°$	$330°-380°$
	$\frac{\Delta\theta_{abnormal}}{\Delta\theta_{normal}}$ (calculated)	$\frac{388°}{385°}=1.01$	$\frac{475°}{405°}=1.16$	$\frac{601°}{427°}=1.41$	$\frac{1307°}{1181°}=1.10$
~ 4300	$\frac{\Delta\theta_{Tucuman}}{\Delta\theta_{Boulder}}$ (observed)		$\frac{120°-140°}{180°-210°}=0.57-0.78$		
	$\frac{\Delta\theta_{abnormal}}{\Delta\theta_{normal}}$ (calculated)		$\frac{170°}{251°}=0.68$		

Table 2

Observed and calculated values of the size of the diurnal phase changes.

第2部 Anomalous Phase Changes of Transequatorial VLF Radio Waves During Geomagnetic Storms

by

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Abstract

The eight months data of the relative phase of VLF signals, NWC (22.3 kHz, Australia), observed at Uji, Japan, are analysed in order to detect geomagnetic storm effects on the low latitude lower ionosphere. Two anomalous phase decreases are found in the nighttime in association with the main phase of large geomagnetic storms. The corresponding changes in the ionosphere are discussed on the assumption that there are the first and the second mode in the nighttime earth-ionosphere waveguide. The situation is very complicated because the propagation parameters vary along transequatorial paths but it is likely that the observed phase changes correspond to an increase of the ionospheric reflection height.

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Introduction

It has been pointed out by many authors that the lower ionosphere at the middle and the higher latitude is disturbed during geomagnetic storms [Knuth and Lauter, 1964; Lauter and Knuth, 1967; Lauter and Nitzche, 1967; King and Fooks, 1968; and Belrose and Thomas, 1968]. This problem has been studied mainly by observing the changes in the field strength and the relative phase of LF and VLF radio waves which are suitable for detecting the small ionization changes in the lower ionosphere. The effects of geomagnetic storms on the lower ionosphere are classified into two parts. The one is the "primary storm effect" which occurs during the main phase of a storm and is characterized by the rapid and deep fading of the signal strength and the phase advance corresponding to the depression of the equivalent reflection height. The other is the "storm after-effect" in which the absorption of the signals is increased several days after a storm and sometimes continues for 10 days or more. Although these effects at LF and VLF can be detected only in the nighttime, the storm after-effects have been observed even at midday by MF and HF absorption measurements. This means that the ionospheric changes during geomagnetic storms reach at least the level of the reflection height of MF and HF in the daytime and of VLF and LF in the nighttime.

All of the observations which have been reported so far on geomagnetic storm effects on the lower ionosphere are limited to the middle and higher latitudes. The behaviors of the low latitude lower ionosphere during geomagnetic storms have not been known yet.

We have been continuously observing the field strength and the relative phase of the frequency stabilized VLF signals (NWC; 22.3 kHz, 1 MW) from North West Cape (Geographic coord: 114°10' E, 21°49' S; geomag. lat: 32.3° S), Australia, at Uji (Geographic coord: 135°47' E, 34°54' N; Geomag. lat: 23.3° N), Kyoto, Japan and detected unusual phase changes during two comparatively large geomagnetic storms. Since the most of the path from NWC to Uji lies in the low latitude region, these unusual phase behaviors seem to show that the electrical conductivity distribution of the lower ionosphere may change even at the low latitude as well as at the middle and the high latitude region during geomagnetic storms.

Observational Results

The VLF station, NWC, began to transmitt the phase stabilized signals in September, 1967. The relative phase and the field strength of this signals have been continuously monitored at Uji, Kyoto, Japan, by the phase locked VLF receiver since June, 1968. The path length between NWC and Uji is about 6800 km. As the most of the path lies in the low latitude region, it is suited for detecting ionization changes peculiar to the low latitude lower ionosphere. In this paper, the data obtained from June, 1968, to February 1969 are analyzed in order to study whether any changes occur in the low latitude lower ionosphere during geomagnetic storms.

Table 1 is the list of the geomagnetic storms and the associated anomalous phase changes occuring for the period of the analysis. It is seen that two anomalous phase changes occurred in association with the two largest geomagnetic storm groups.

Figure 1 shows the diurnal phase variations from Oct. 27 to Nov. 7, 1968. The inclination of the rectangles drawn by chain line shows a drift of the reference oscillator. Usually the phase advances during a sunrise and retards during a sunset corresponding to the changes of the ionospheric equivalent reflection hight. The humps seen in the daytime are SPA's (sudden phase anomalies) caused by an ionization increase due to solar flares.

On Oct. 27 and 28, the diurnal phase variations are normal but from Oct. 29 the nighttime phase deviates from the normal diurnal variations. Although some of small deviations could not be distinguished from always existing fluctuations, shaded regions show undoubtedly meaningful deviations from the normal state. At a glance of Figure 1, it can be easily seen that the deviations occur mainly in the sense to make the phase retard.

Figure 2 shows the nighttime phase variations and the diurnal variations of the geomagnetic H component observed at Aso (geomag. lat: 22° N), Japan, from Oct. 28 to Nov. 4, 1968. On Oct. 29, ssc (storm sudden commencement) occurred at 09^h09^m UT and the phase deviation began from about 15^h when large disturbances appeared on the magnetogram. It became largest around the time when H reached the minimum level. On Oct. 30, the geomagnetic field was not so active and the phase deviation was also small. A typical magnetic storm occurred on Oct. 31. After ssc at $08^h 59^m$ and the initial phase of about 5 hours followed the large main phase during which the geomagnetic H component decreased by 256 γ below the normal level. The phase began to decrease with the begining of the main phase and the maximum deviation reached about 10 μ sec. In the local daytime on Nov. 1, the geomagnetic field once recovered nearly to the normal level but was disturbed again from the evening to the night. Here again the phase deviation seems to be associated with the decrease of the geomagnetic H component. Nov. 2, 3 and 4 are the recovery periods to the normal state for both the geomagnetic field and VLF phase and the deviations are very small.

Figure 3 is the second example, the VLF phase and the geomagnetic variations during the nighttime from January 31 to February 5, 1969. A geomagnetic ssc occurred at $15^h 01^m$ on February 2. The VLF phase began to decrease from the normal nighttime level at the almost same time with the begining of the main phase. The maximum phase deviation is about 10 μ second. The deviation of both the phase and the geomagnetic field becomes smaller day after day as shown by the record on Feb. 3, 4 and 5.

For both storms, anomalous changes in the field strength corresponding to the phase deviations could not be identified because of the large day-to-day variability. The storm aftereffects also could not be detected by our analysis.

Discussions

A part of the energy transmitted from NWC might penetrate through the ionosphere and be guided along a geomagnetic field line as a whistler mode and reach the magnetic conjugate point in the northern hemisphere. Since the magnetic conjugate point of NWC is about 1700 km northwest from Uji, we might observe the whistler mode signals in addition to the direct earth-ionosphere waveguide modes. It has been pointed out that the occurrence rate of natural whistlers increases after geomagnetic storms [for the reference on this subject, see Okuzawa et al. 1971]. The anomalous variations described above, therefore, might be caused by the enhanced whistler mode signals. The whistler mode signals from a frequency stabilized transmitter, however, usually suffer Doppler shift and the interference with the direct waveguide mode would cause a beat of a period of a second to ten minutes [for example, McNeil and Allen, 1964]. Such a beat type variation is not seen in Figures 1-3. Thus the phase changes in this paper should be interpreted in terms of variations of the direct waveguide modes themselves.

If only the first order mode exists in the earth-ionosphere waveguide and its phase velocity varies from V to V', the observed phase change, $\Delta\theta$, is given by

$$\Delta\theta = \frac{fx}{2\pi} \left(\frac{1}{V'} - \frac{1}{V} \right) \tag{1}$$

where f and x are the wave frequency and a propagation path length, respectively. The phase velocity depends on the ionospheric model. If we use the phase velocity given by Bates and Albee [1965] for the sharply bounded spherically concentric earth-ionosphere waveguide, the phase decrease of 10 μ sec corresponds to a 3-4 km increase of the ionospheric reflection height. The sharply bounded ionosphere model, however, is insufficient for the radio wave reflection of a long wave length from the lower ionosphere varying rapidly with a height. We must, therefore, use the phase velocity derived for the height varying ionosphere such as the exponential model given by Wait [1962]. Moreover, there are some evidences showing the existence of two modes in the nighttime waveguide [Crombie, 1962].

When there are the first and the second order mode, the resultant wave field is given by

$$E = E_{01}\sin(\omega t + \theta_1) + E_{02}\sin(\omega t + \theta_2) = E_0\sin(\omega t + \theta) \quad (2)$$

$$\left.\begin{aligned} E_0 &= (E_{01}{}^2 + E_{02}{}^2 + 2E_{01}E_{02}\cos(\Delta\theta))^{\frac{1}{2}} \\ \theta &= \theta_1 + \alpha \\ \tan\alpha &= E_{01}\sin(\Delta\theta)/(E_{01} + E_{02}\cos(\Delta\theta)) \\ \Delta\theta &= \theta_2 - \theta_1 \end{aligned}\right\} \quad (3)$$

where E_0, ω, and θ are the amplitude, the angular frequency and the phase of the wave, and suffixes 1 and 2 denote the first and the second order mode, respectively. If E_{01} and E_{02} are assumed to be time-independent, the rate of the time variation of the resultant phase becomes, after some manipulations, as follows

$$\frac{d\theta}{dt} = A_1 \frac{d\theta_1}{dt} + A_2 \frac{d\theta_2}{dt} \tag{4}$$

where

$$A_1 = \frac{1 + R\cos\Delta\theta}{1 + 2R\cos\Delta\theta + R^2}, \quad A_2 = \frac{R + \cos\Delta\theta}{1 + 2R\cos\Delta\theta + R^2}$$

$$R = \frac{E_{02}}{E_{01}}. \tag{5}$$

If R is larger than unity, A_2 is positive and the sign of the second term of eq. (4) is the same as that of $\frac{d\theta_2}{dt}$. The sign of the first term, however, is not always the same as that of $\frac{d\theta_1}{dt}$, because the coefficient A_1 may take both negative and positive values depending on $\Delta\theta$. Therefore, θ does not always increase (or decrease) even if both of θ_1 and θ_2 increase (or decrease). Since $\Delta\theta$ in the uniform earth-ionosphere waveguide is expressed as [Lynn, 1970]

$$\Delta\theta = 2\Pi\frac{x}{D} + \arg\left(\frac{\Lambda_{N2}}{\Lambda_{N1}}\right) \tag{6}$$

where Λ_{N1} and Λ_{N2} are the excitation factor of the nighttime first and second order modes and D is the interference distance [Crombie, 1964] given by

$$D = f\,\frac{V_{N1}V_{N2}}{V_{N2} - V_{N1}}, \tag{7}$$

the sign of $\frac{d\theta}{dt}$ depends upon a propagation path length x.

The situation is further complicated by the fact that the interference distance, D, seems to vary along propagation paths crossing the geomagnetic equator [Lynn, 1969, and Araki, 1973].

In this case, equation (5) should be replaced by

$$\Delta\theta = 2\Pi\int_0^x \frac{dx}{D(x)} + \arg \frac{\Lambda_{N2}}{\Lambda_{N1}} . \tag{8}$$

By adopting the model of D(x) which is used in the interpretation of the anomalous diurnal changes of the phase and the field intensity of the transequatorial VLF radio waves [Araki, 1973], we can calculate $\Delta\theta$ for NWC-Uji path and then the coefficients A_1 and A_2 from equation (5). The results is that A_1=-0.19 and A_2=1.19. Thus the decrease in θ at the initial stage of the disturbances might be mainly due to a decrease of θ_2 unless $\frac{d\theta_2}{dt}$ is much smaller than $\frac{d\theta_1}{dt}$. If $\Delta\theta$ does not change so greatly with the progress of the disturbance, the time variation of A_1 and A_2 would also be small. In this case the observed phase retardation might be caused by a decrease of θ_2 through a whole period of the disturbance. Since a phase decrease of a mode usually corresponds to an increase of the ionospheric reflection height, it is likely that the lower ionosphere might rise up during severe geomagnetic storms. For the more precise determination of the change in the ionosphere, we need the more detailed knowledge about the relation between the phase change due to an ionospheric reflection and the height distribution of the electrical conductivity, because the reflection of VLF radio waves depends not only on the electrical conductivity of the lower ionosphere but also on its vertical gradient. The horizontal inhomogenities of the propagation parameters existing along the transequatorial propagation path would require also the phase observation at several points on the path.

It is well known that the ionospheric F-region is disturbed world-widely during geomagnetic storms [see the recent review paper by Matsuura (1971)]. The causal relationship is very complicated but it could be roughly said that the F-region storm is the production and the worldwide redistribution of electrons caused by the enhanced solar wind energy which flows down mainly into the high latitude ionosphere as the forms of particle precipitation, hydromagnetic waves, the electric field and heat conduction. As a process leading to the electron redistribution the change of the global atmospheric wind system due to a temperature increase is proposed in addition to the electric drift and the ionization. This process might change the distribution of the electrical conductivity (determined mainly by the electron density and the collision frequency) even in the low latitude lower ionosphere, while the drift motion by the electric field would be greatly reduced by the dominant collision. Though the ionization by particle precipitation has been expected so far to occur in the high latitude region, the recent discovery of the subtropical radiation belt [Hill et al., 1970; Heikkila, 1971; Kohno, 1973 and Hayakawa et al., 1973] is interesting as an ionizing agency in the low latitude region.

Acknowledgements

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Figure Captions

Fig. 1. Diurnal phase variations of NWC signals (22.3 kHz) observed at Uji, Japan, from Oct. 27 to Nov. 7, 1968. The phase advances upwards. The humps in the daytime are the sudden phase anomalies caused by the solar flare X-ray. The dark portions show undoubtedly meaningful deviations from the normal diurnal variation pattern. The dotted portions also seem to be meaningful.

Fig. 2. Nighttime phase variations of NWC signals (22.3 kHz) observed at Uji, Japan, and the geomagnetic H-component at Aso from Oct. 28 to Nov. 4, 1968. The phase and H increase upwards. The meaning of the dark and dotted portions is the same as that of Fig. 1.

Fig. 3. Nighttime variations of the phase of NWC signals (22.3 kHz) observed at Uji and geomagnetic H-component at Aso, Japan, from Jan. 31 to Feb. 5, 1969. The meaning of the dark and dotted portions is the same as that of Fig. 1.

Table 1

List of geomagnetic storms at Kakioka, Japan, and the associated anomalous phase changes of NWC signals for the period of the analysis.

Date	Time of SC	ΔH(SC)	ΔH(MP)	Anomalous Phase Change
Jun. 10-14 1968	$10^{day}21^{h}54^{m}$	9^{γ}	114^{γ}	NO
14-15	14 03 42	4	85	NO
Jul. 25-28	25 16 17	10	68	NO
Jul. 9-12	99 21 54	2	88	NO
13-15	13 16 13	35	116	NO
Aug. 23-	23 17 14	10	61	NO
Sep. 6- 8	6 14 38	16	122	NO
30-	30 23 45	20	-	NO
Oct. 2- 3	2 00 18	9	96	NO
6- 8	6 06 28	27	76	NO
11-14	11 22 00	-	98	NO
28-	28 21.5			
29-	29 06 45	11		
29-	29 09 09	30	125	YES
31-	31 08 59	45	256	YES
Nov. 1- 4	1 09 16	13	177	YES
16-19	16 09 16	19	199	NO
20-21	20 09 04	38	101	NO
Dec. 5- 6	5 06 33	13	55	NO
24-25	24 22.3		69	NO
Jan. 7- 8 1969	7 03 22	11		NO
24-	24 10.5			NO
25-27	25 00 36	3	81	NO
Feb. 2- 5	2 15 01	31	203	YES
10-12	10 20 24	6	162	NO
26-	26 01 57	15	112	NO
27-	27 03 07	7		NO
28-28	28 04 23	27		NO

Amplitudes of the sudden commencement and the main phase are denoted by ΔH(SC) and ΔH(MP), respectively.

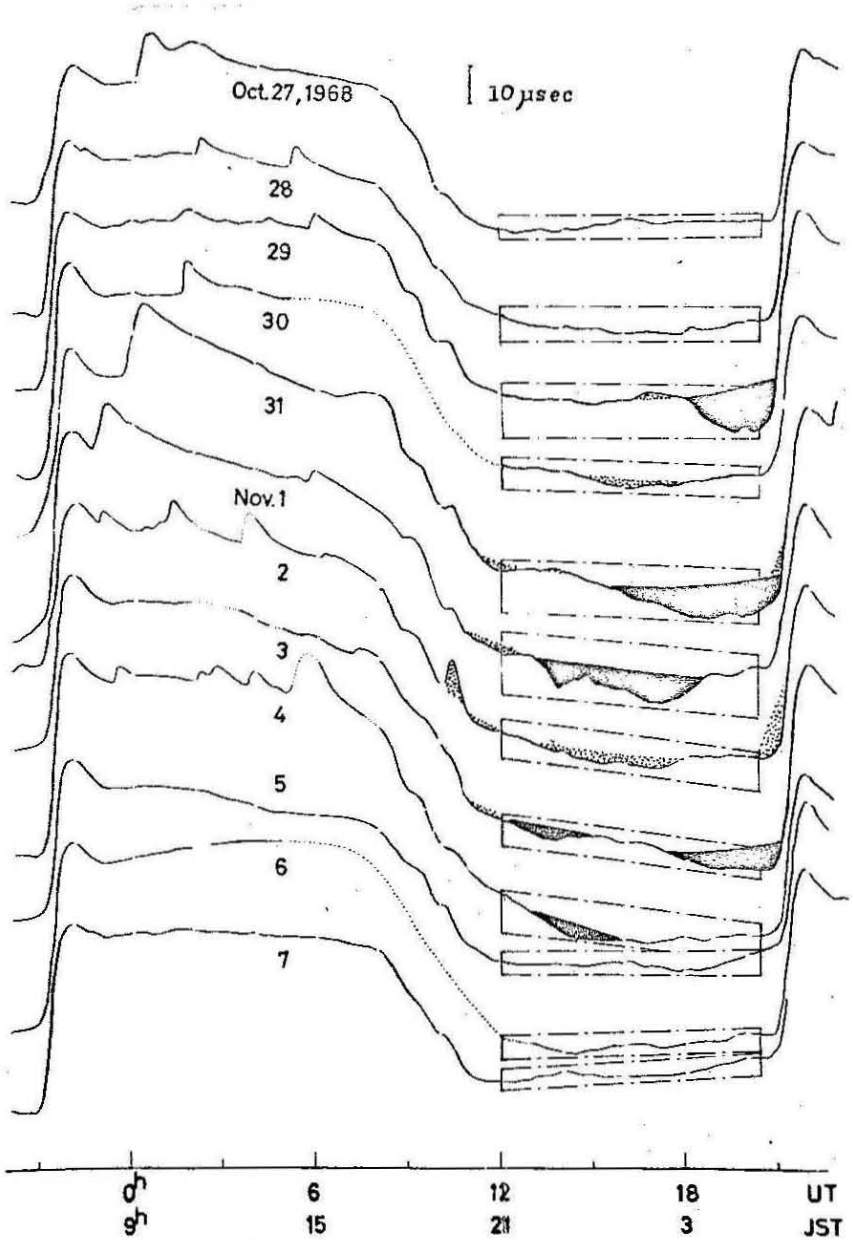
Oct.27,1968
10 μsec
28
29
30
31
Nov.1
2
3
4
5
6
7
0h 6 12 18 UT
9h 15 21 3 JST

Fig.1

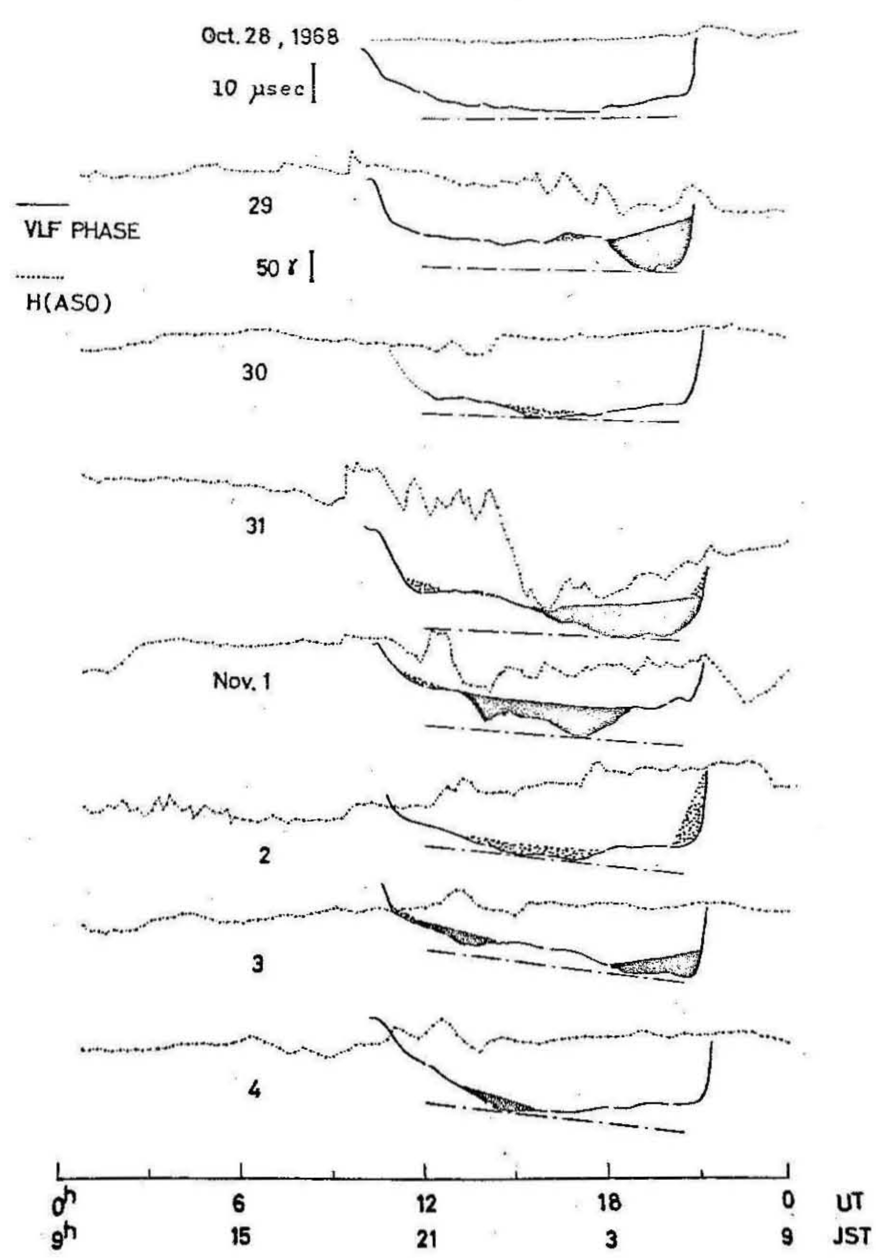
Oct.28, 1968
10 μsec
29
VLF PHASE
50 γ
H(ASO)
30
31
Nov.1
2
3
4
0h 6 12 18 0 UT
9h 15 21 3 9 JST

Fig.2

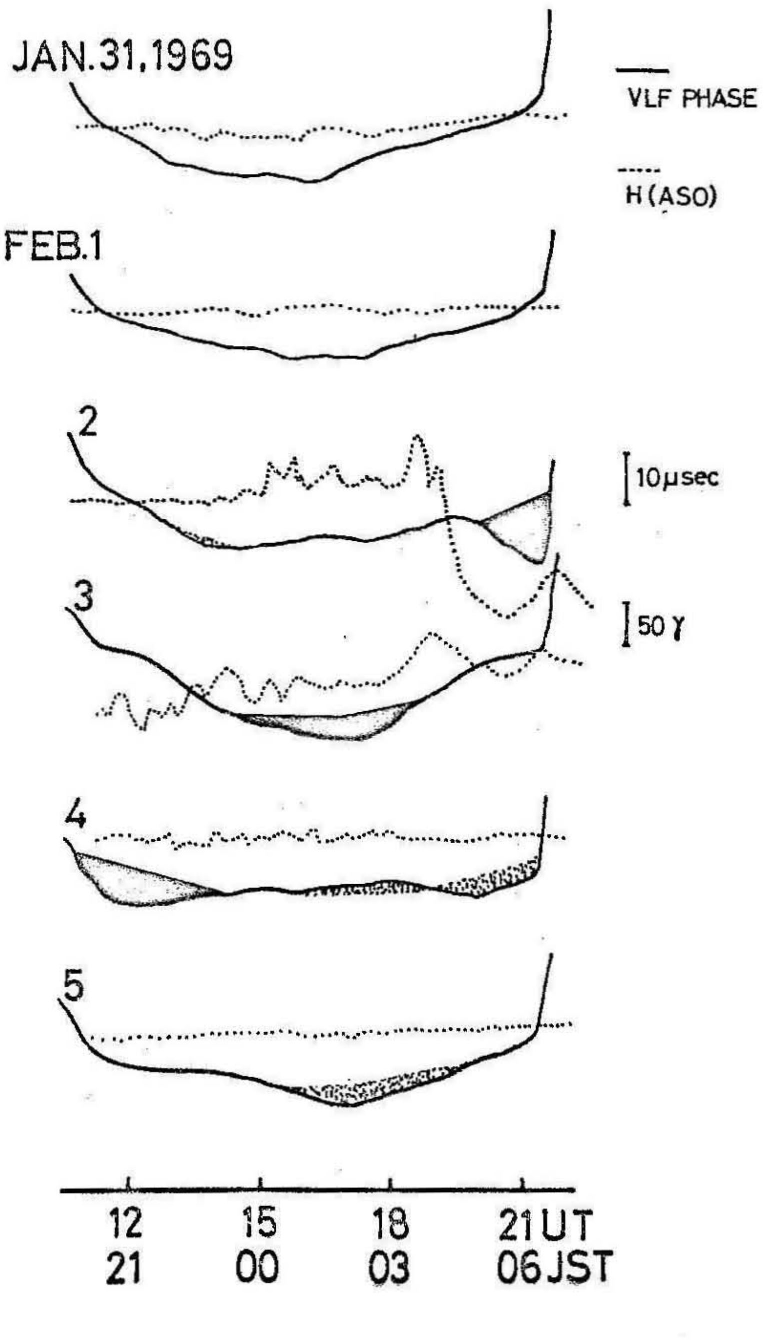
JAN.31,1969
VLF PHASE
H (ASO)
FEB.1
2
10μsec
3
50γ
4
5
12
15
18
21UT
21
00
03
06JST

Fig.3